SOFT, Aix-en-Provence, September 2026

Plasma system in fusion plant design: challenges, uncertainties and perspectives

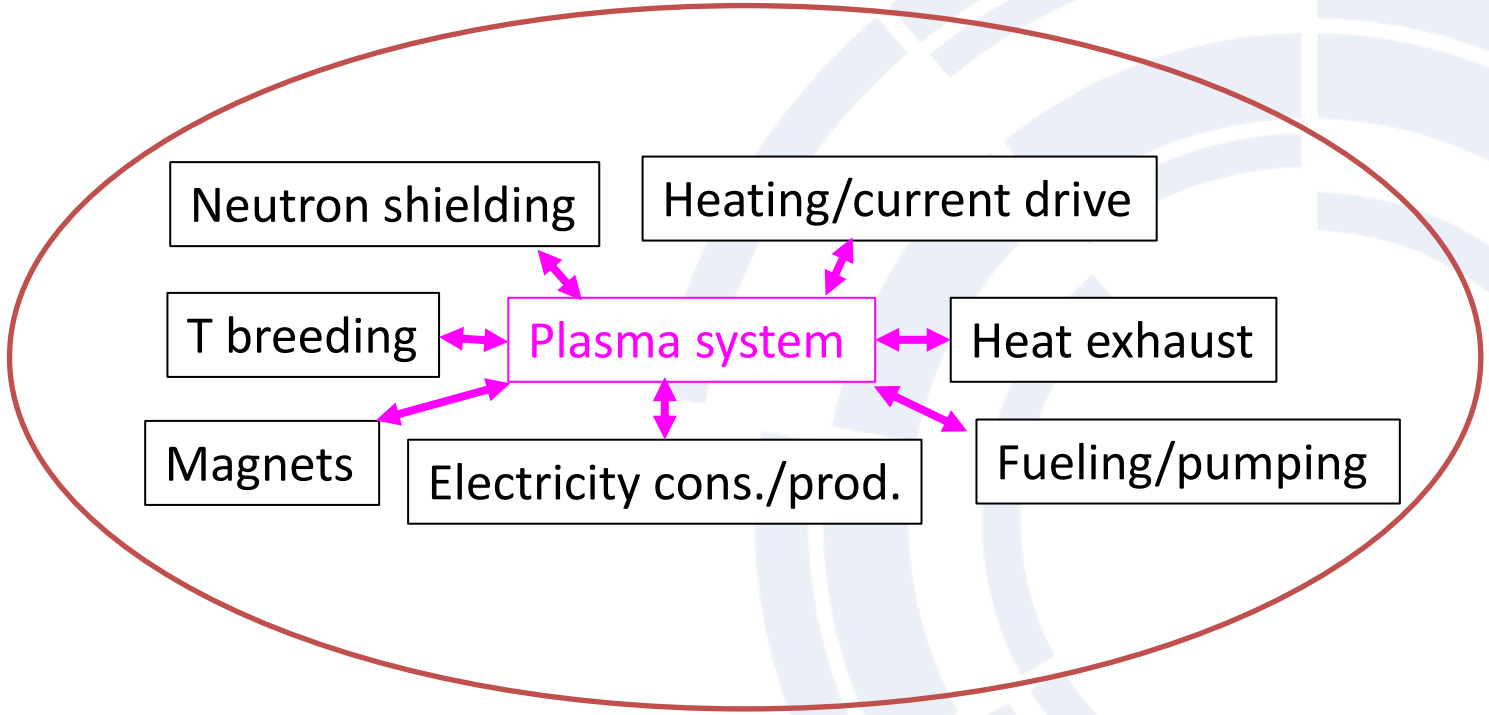
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[10]UKAEA, Culham Science Centre, Oxfordshire, United Kingdom of Great Britain and Northern Ireland

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Plasma: a central system for fusion plant design

System codes: manage interfaces between plasma system and engineering systems



The example EU-DEMO 2024 baseline using system code PROCESS [Coleman NF2025]

Optimization on :

- net electricity power $P_{el,net} \geq 350$ MWe
- pulse duration ≥ 2 hours
- Divertor protection $q_{div,outer} \leq 50$ MW/m^2 during accidental re-attachment

Main fusion plant performances how do they relate to Plasma System?

- **Net electric power** related to **fusion power** delivered by the plasma system
- **Pulse duration** related to **plasma resistivity, non-inductive currents** (Bootstrap, wave driven current efficiency)
- **In vessel components protection** related to **higher Z ions content / radiated power** reducing divertor heat fluxes

Outline

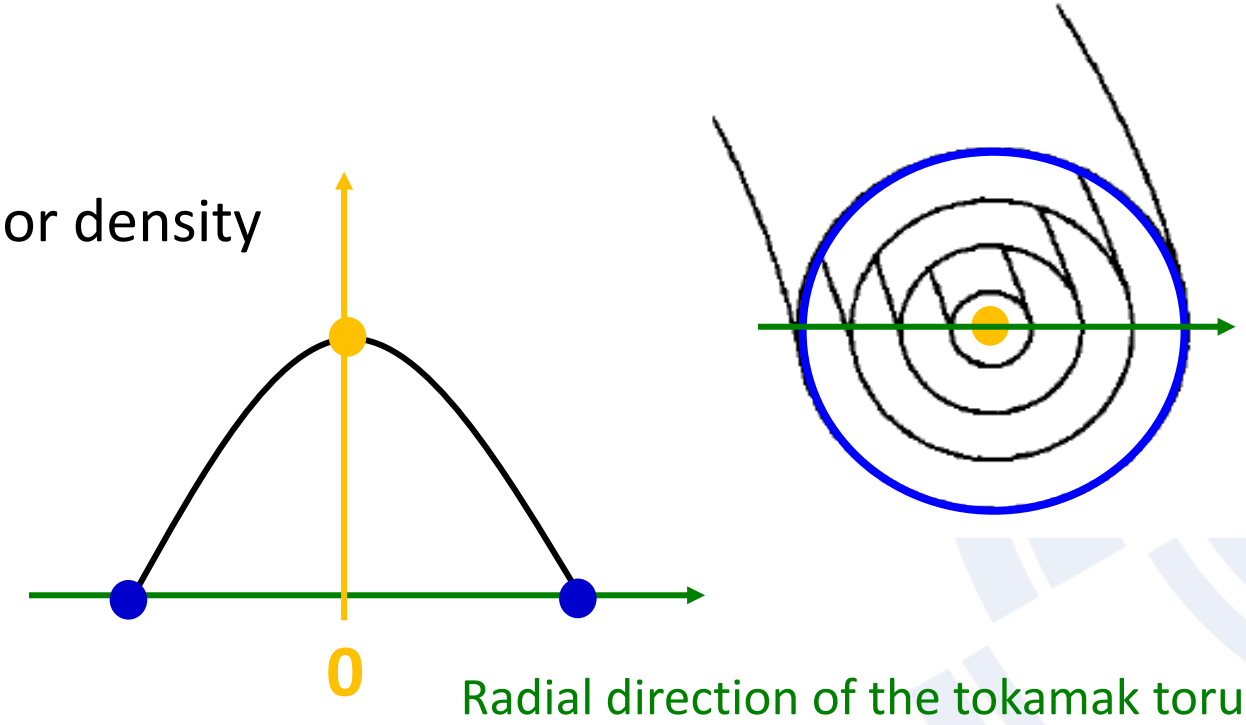
- How fusion plant performances are estimated? The example of the fusion power
- High Fidelity Integrated Modelling of the plasma system
- Validation and verification of High Fidelity Integrated Modelling
- Impact on the EU-DEMO baseline performances: fusion power, pulse length
- Lessons learnt, way forward

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- **How fusion plant performances are estimated? The example of the fusion power**
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How to calculate the fusion power?

- $P_{fus} \propto n_{fuel}(0)^2 T_i(0)^2$ so the D and T density and their temperature on the magnetic axis are key quantities



- 1D profiles of temperature and density are mandatory to calculate P_{fus}

Two approaches to predict $n_{fuel}(0)$ and $T_i(0)$ hence P_{fus}





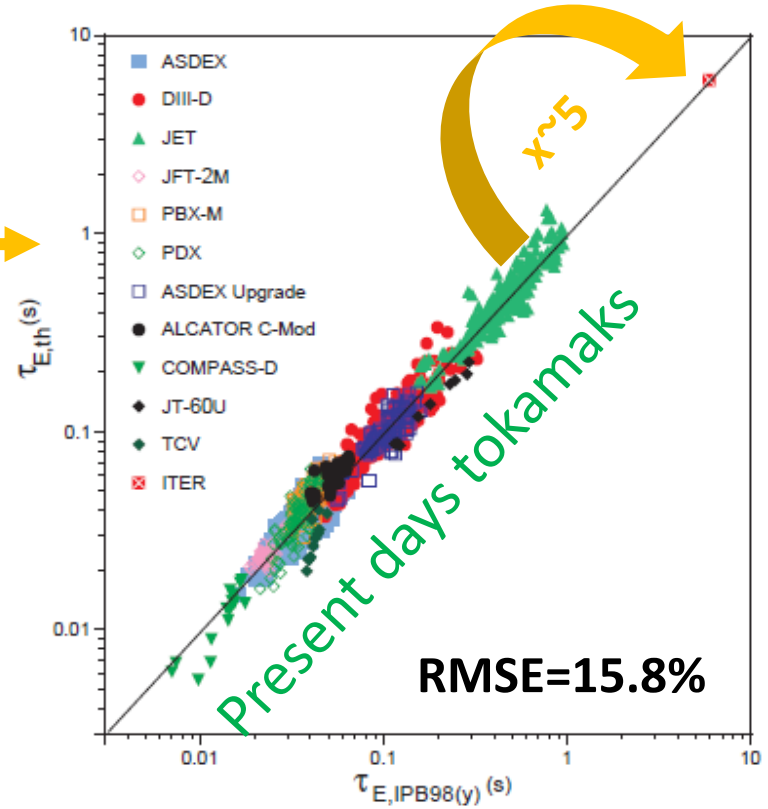
How $n_{fuel}(0)$ and $T_i(0)$ are estimated in system codes?



- **From 0D quantities:** total energy and particle contents
- From 0D quantities, values on magnetic axis obtained thanks to free ad-hoc parameters
- $P_{fus} \propto n_{fuel}(0)^2 T_i(0)^2$ depends on **3 scaling laws** (energy, pedestal, density) and **13 ad-hoc parameters** (separatrix and pedestal T and n, T_e/T_i, T and n peaking factors)

- **Ex. of 0D energy content estimate** based on Scaling law **qualitative** and **quantitative issues**

	Exp^{al} database	**DEMO class devices**
heating	Externally provided	Dominated by self-heating of alpha power
Main ions	Mostly H, D, some D-T, T [NF 2021]	50/50 D-T



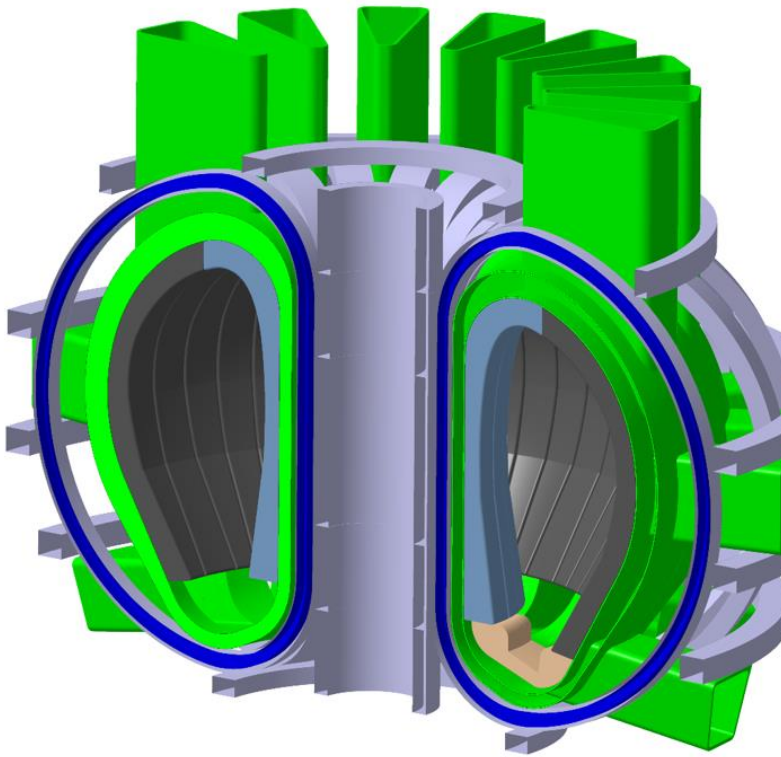
ITPA [NF 1999]

Definition of EU-DEMO 2024 baseline [Coleman NF 2025]

- Using in PROCESS a total of **15 ad-hoc parameters and 5 scaling laws** to compute P_{fus}, pulse length and heat flux on divertor

- EU-DEMO 2024 specificities:
  - reduction of divertor heat loads
  - design margin for epistemic uncertainties: MagnetoHydroDynamic limit ($q_{95} \geq 3.6$ instead of 3)

Parameters	EU-DEMO
$P_{el,net}$ [MW]	350
P_{fus} [GW]	1.6
$P_{aux,ECRH}$ [MW]	40
Q	40
τ_{pulse} [hr]	2
divertor flux* [MW/m^2]	44.3<50
A	2.8
R_0 [m]	8.6
$B_{T,0}$ [T]	4.39
q_{95}	3.6



* if accidental reattachment

Outline

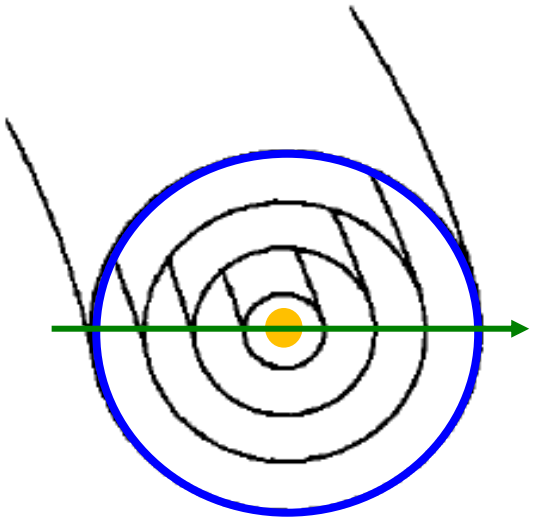
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Example of P_{fus} : How $n_{fuel}(0)$ and $T_i(0)$ should be estimated?

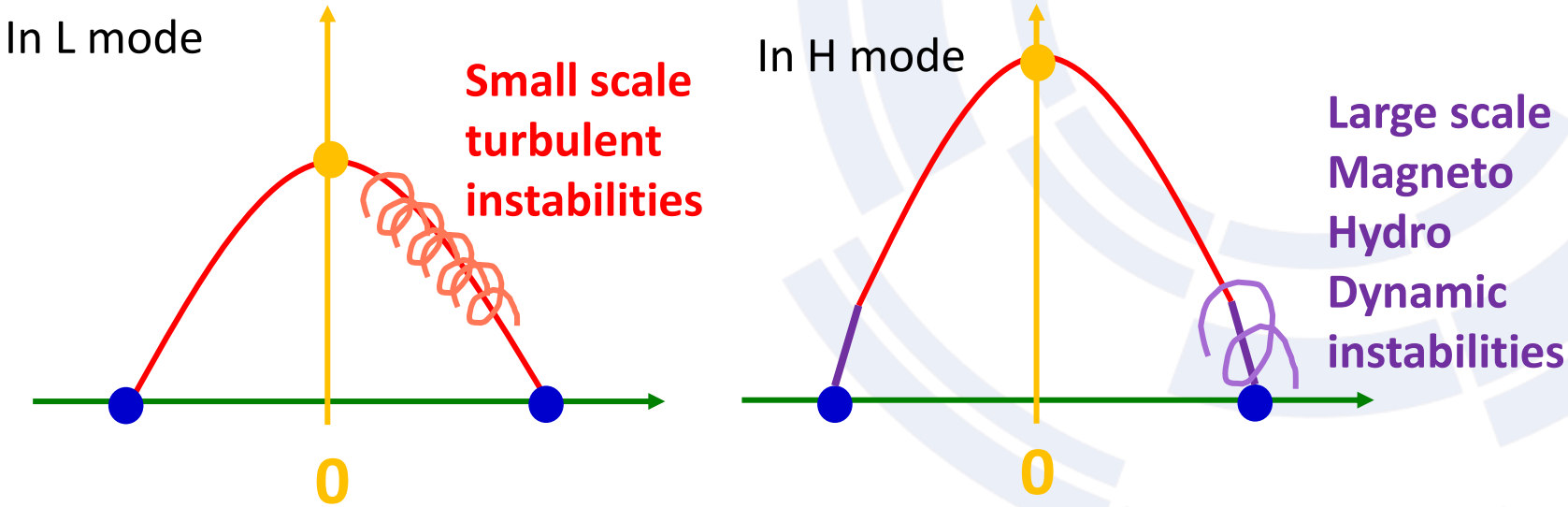


- Turbulence determines the critical gradients of plasma density and temperature ?





Temperature or density radial profiles



How $n_{fuel}(0)$ and $T_i(0)$ should be estimated? Need to integrate turbulent transport models to predict the profiles

Long standing know-how

[F.M. Poli PoP 2018, C. Bourdelle PPCF 2025]

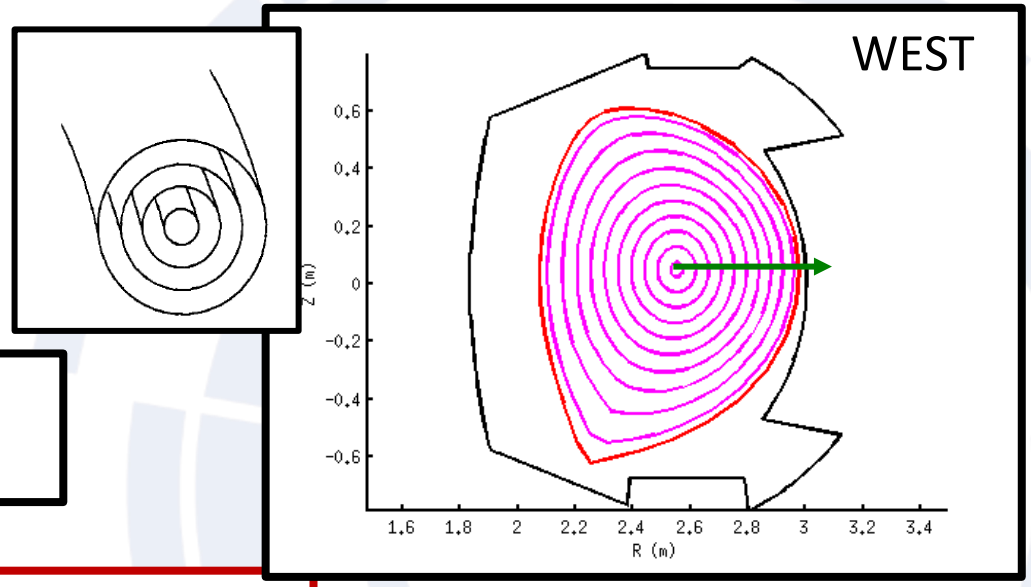
Auxiliary heating, alpha power

D,T fueling/pumping

But also radiative losses due to tungsten, etc

Source/sink modules

magnetic equilibrium

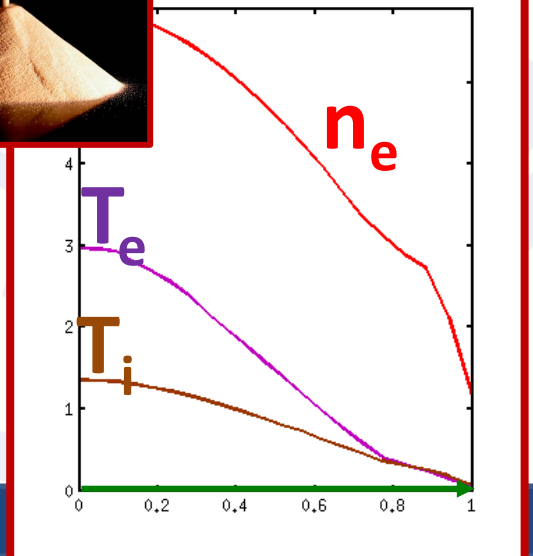


Initial profiles

transport PDE solver $t \rightarrow t + \Delta t$

Predicted temp, density, and rotation profiles





Transport fluxes collisional and turbulent

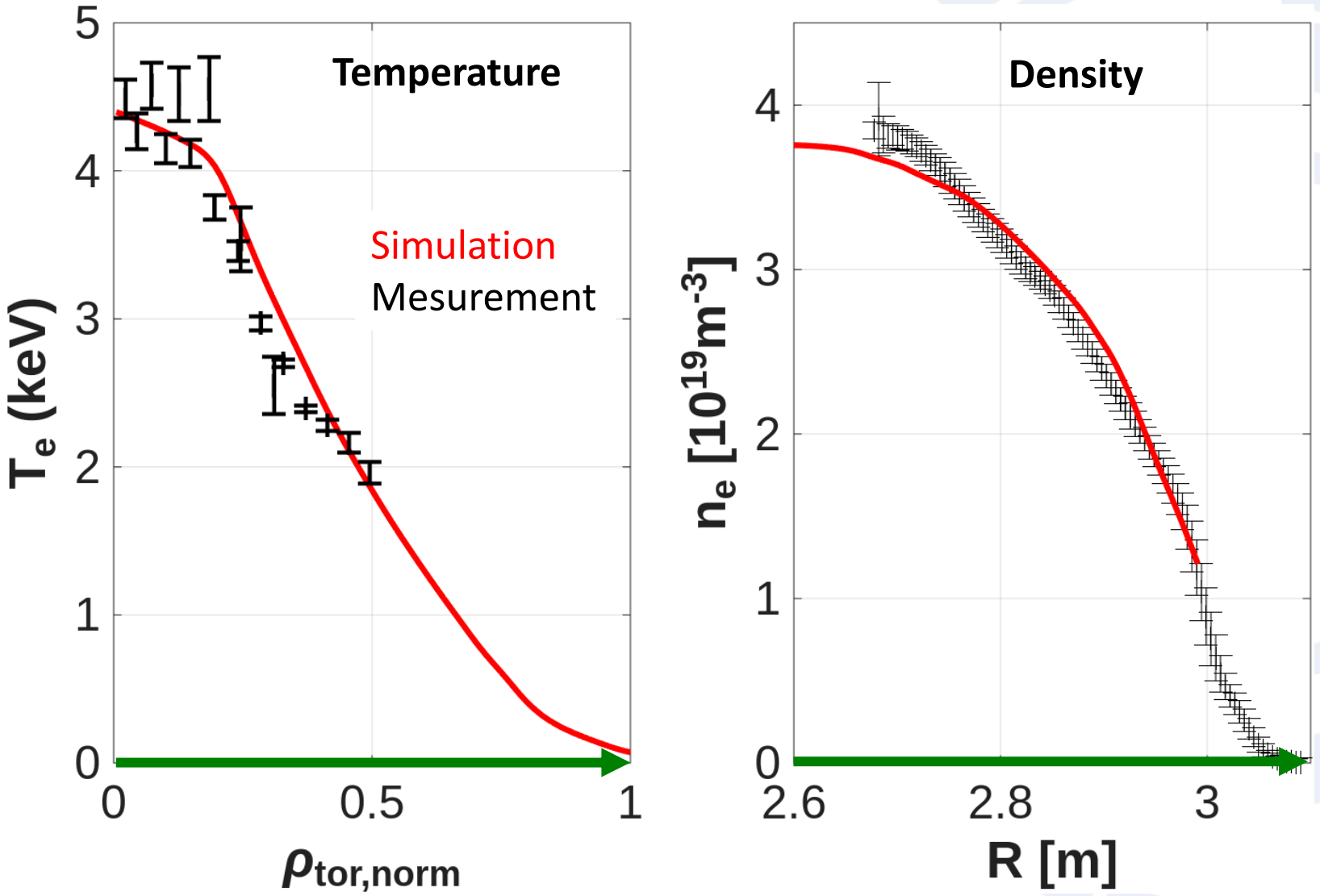


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High fidelity integrated modeling: validation example

WEST
[Fonghetti NF 2025]

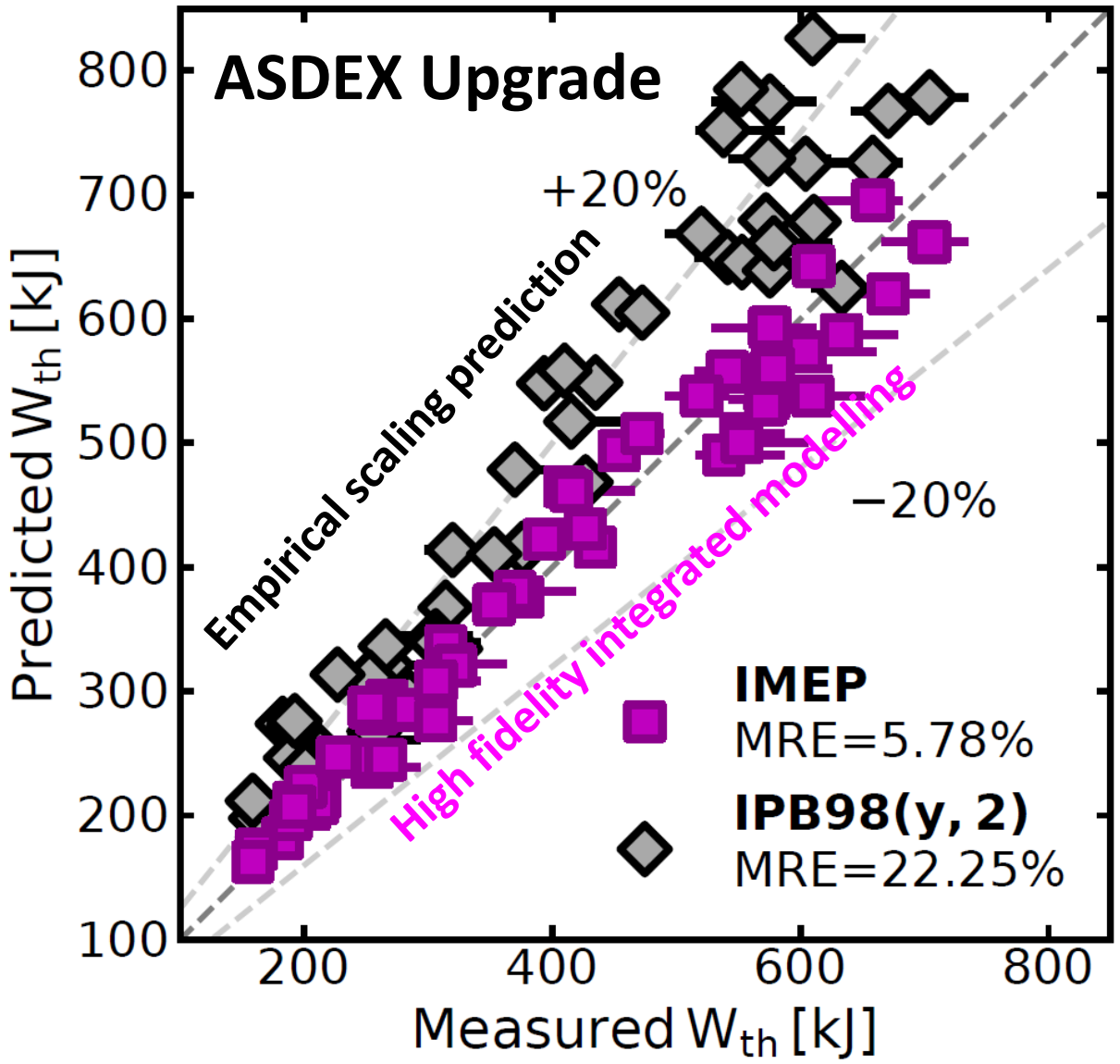


High fidelity integrated modelling: better than empirical scaling laws in predicting energy content

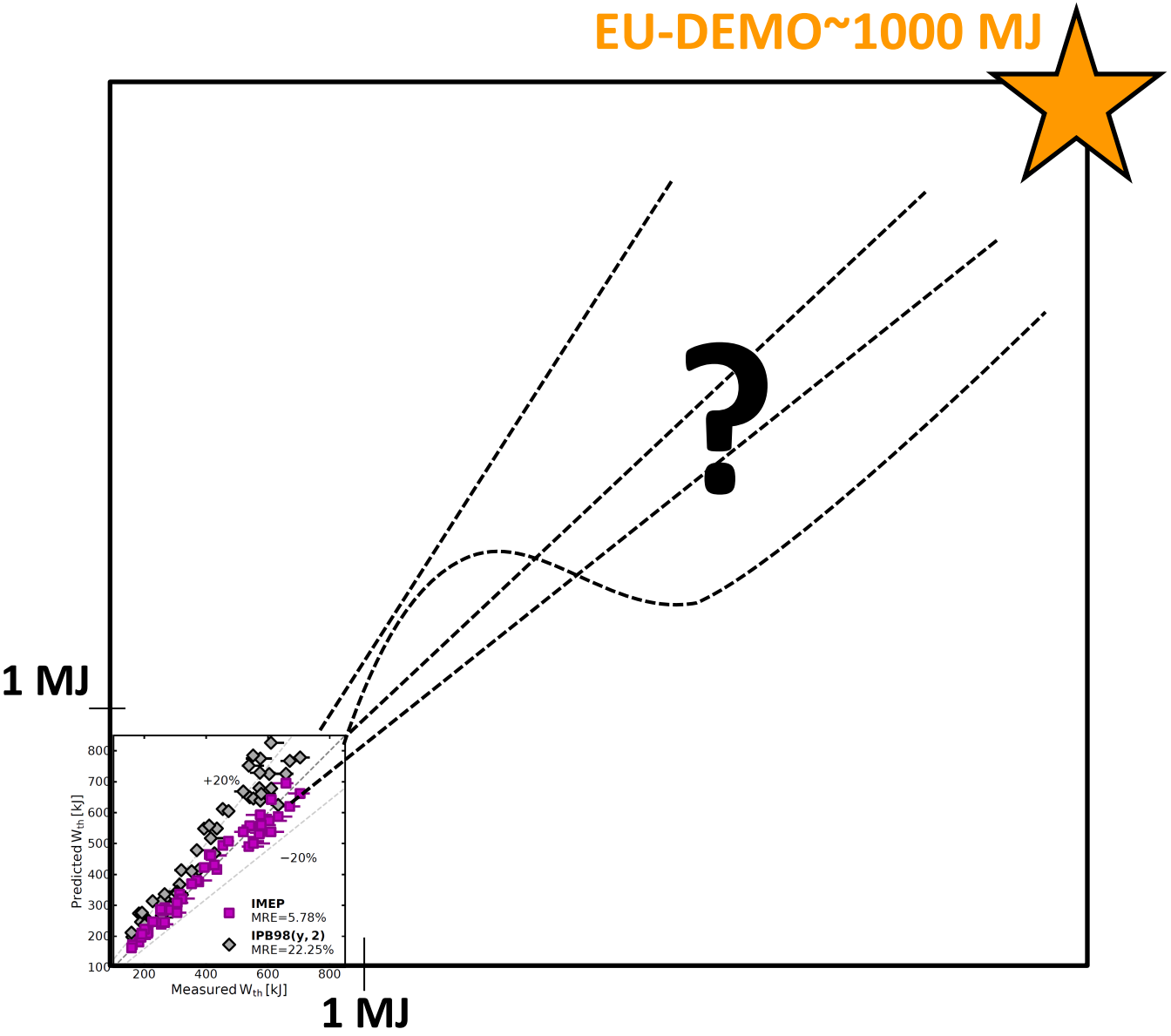
Energy content prediction on ~ 50 H mode plasmas vs measured energy content

[Luda NF 2021]

Multi-tokamak validation review [Bourdelle PPCF 2025]

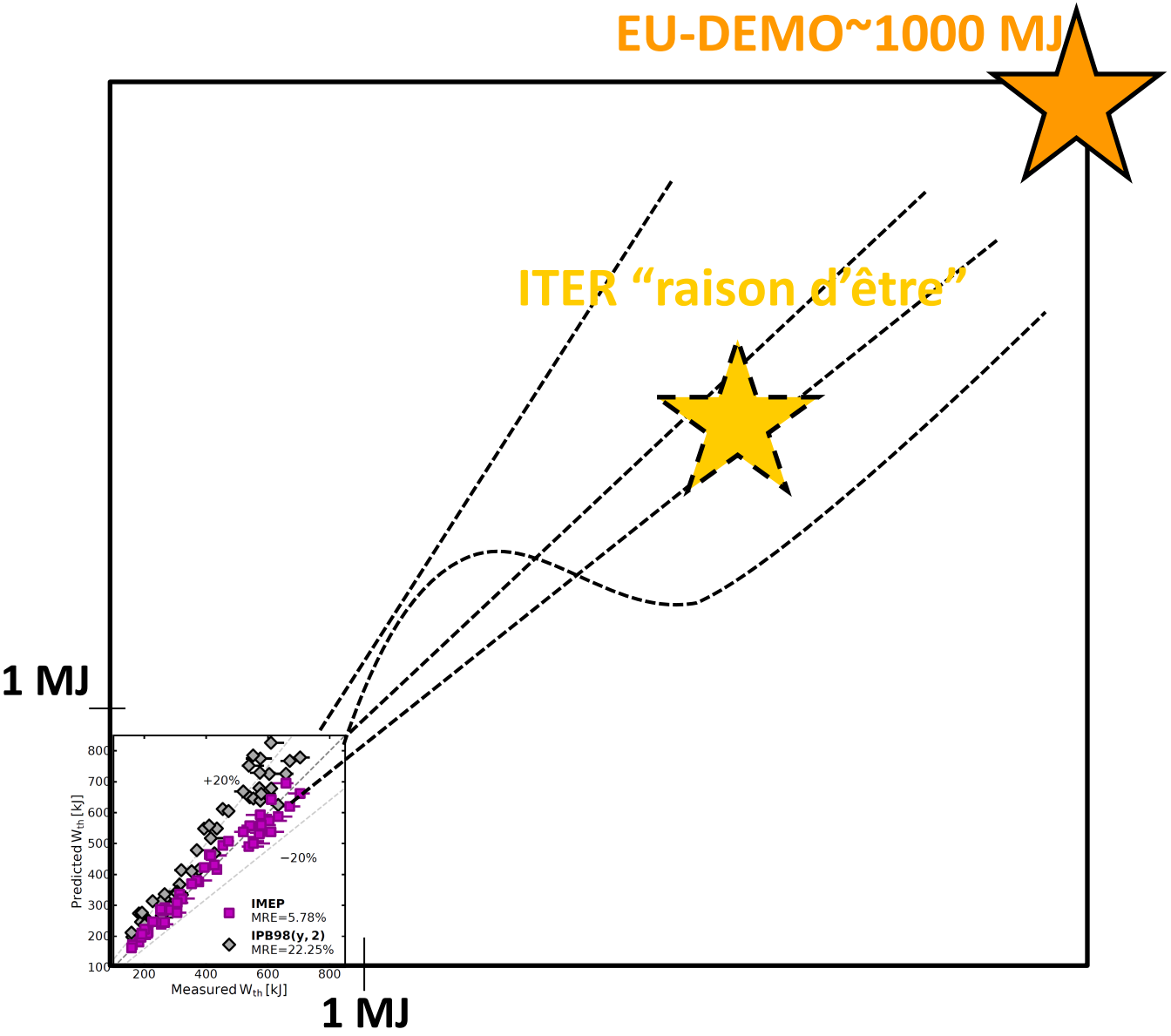


In presence of gap, need validation and verification



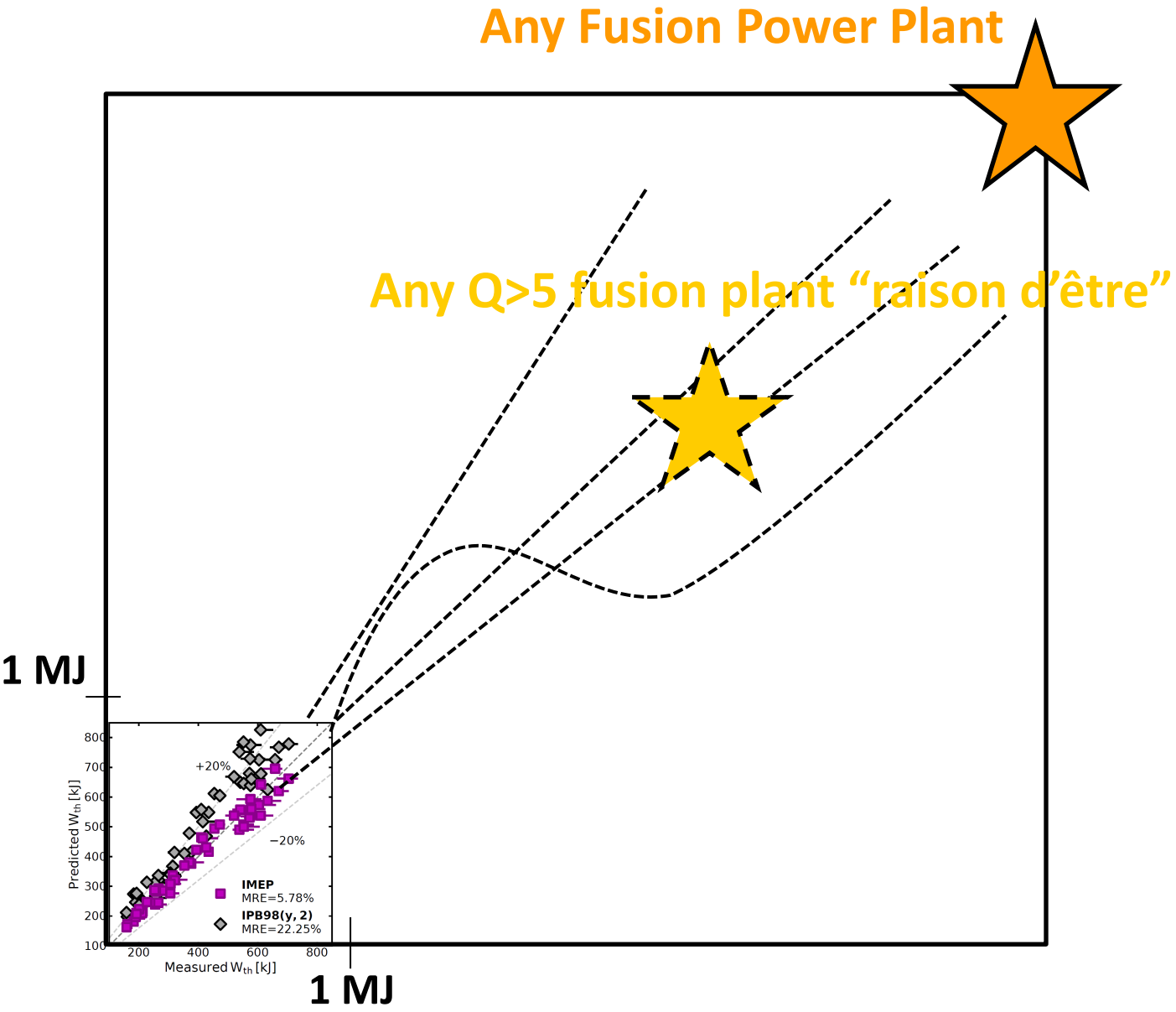
- High Fidelity Integrated Modelling successfully validated on Today's tokamaks: mostly deuterium auxiliary heated plasmas
- Does it extrapolate to DEMO class D-T burning plasmas?

In presence of gap, need validation against burning plasmas



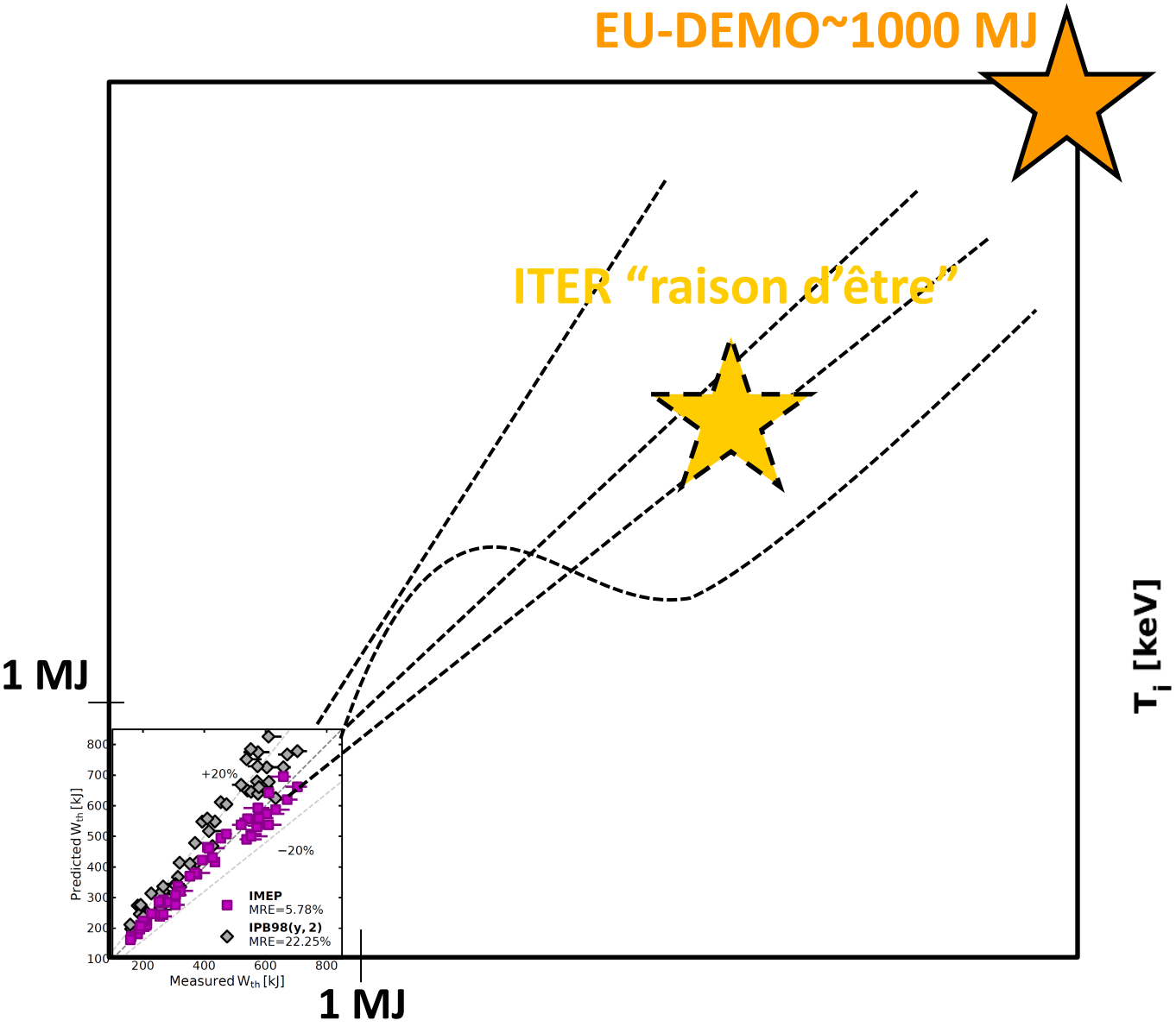
- **Should validate** quasilinear turbulent model **on ITER burning plasma experiments i.e. $P_{alpha} > P_{aux}$**
  $Q=P_{fus}/P_{aux}=P_{alpha}x5/P_{aux}$ > 5 asap

In presence of gap, need validation against burning plasmas

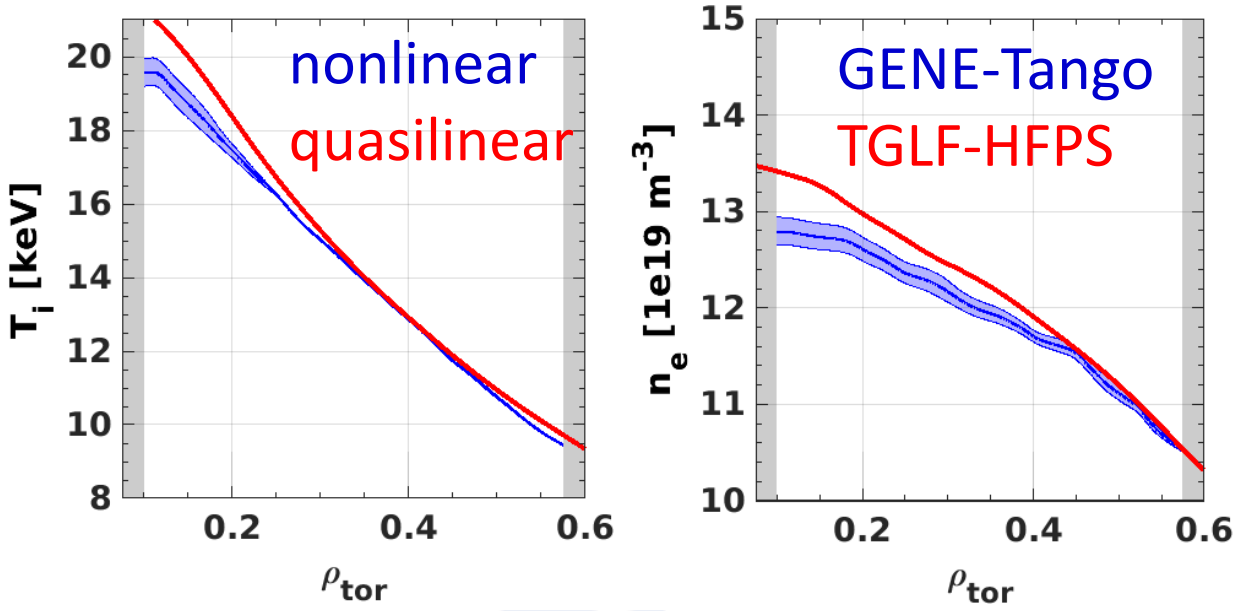


- **Should validate** quasilinear turbulent model **on burning plasma experiments i.e. $P_{alpha} > P_{aux}$ $Q=P_{fus}/P_{aux}=P_{alpha}x5/P_{aux} > 5$** asap

In presence of gap, need verification against highest fidelity models



- **In the meantime verification of high fidelity integrated quasilinear modelling against even higher fidelity nonlinear turbulence model** using GPU accelerated code (GENE-Tango) done on ITER 15 MA



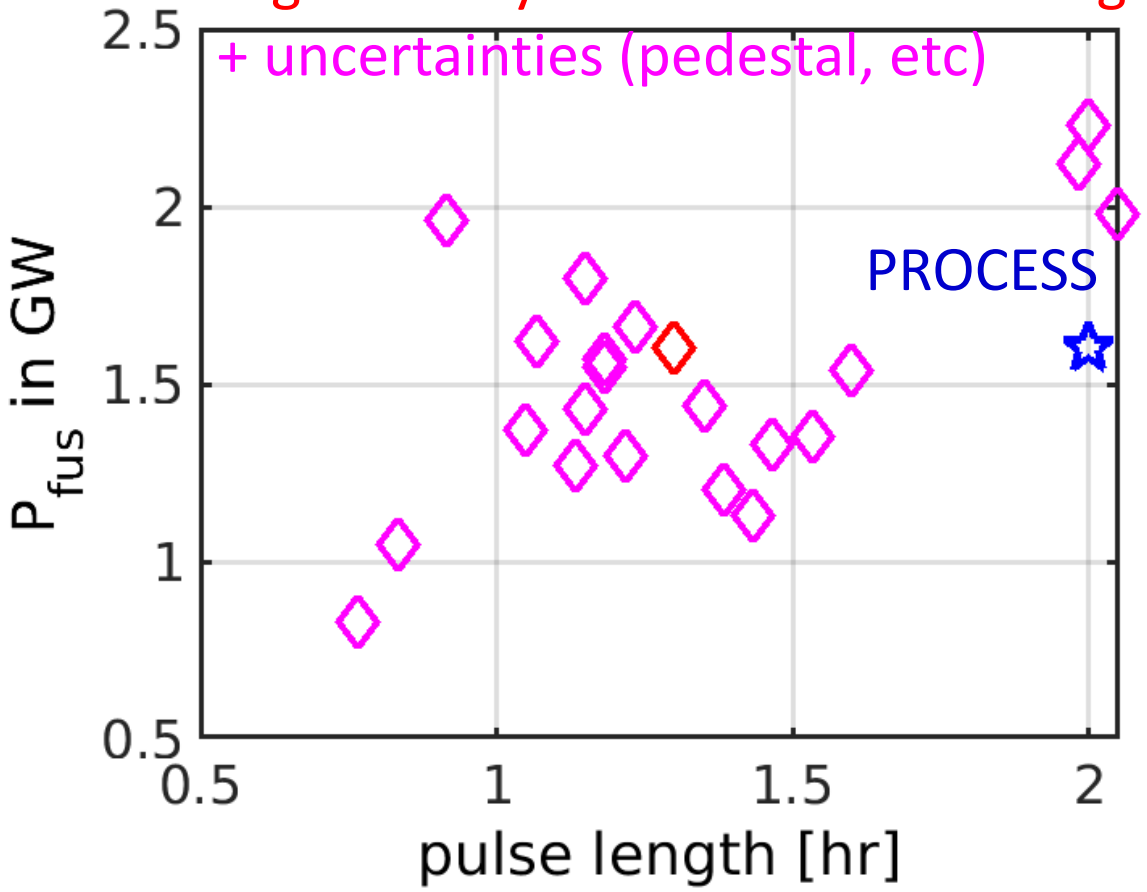
[Di Siena NF2026]

Outline

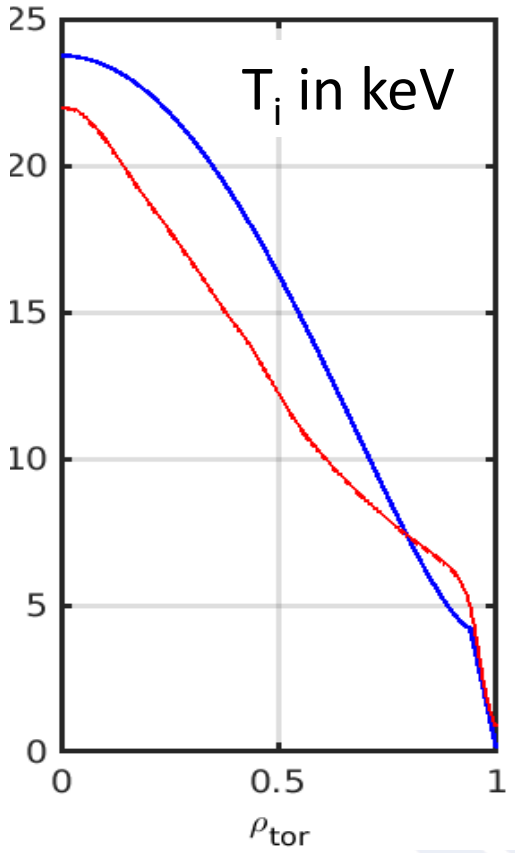
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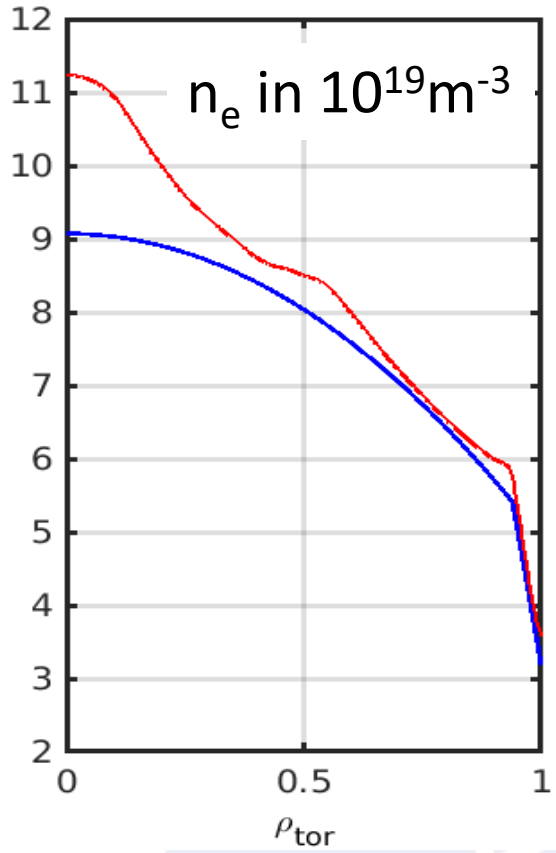
EU-DEMO baseline 2024 [Coleman NF 2025]
System code vs verified high fidelity integrated modelling incl. uncertainties

High Fidelity verified Int. Modelling
+ uncertainties (pedestal, etc)



PROCESS High Fidelity verified Int. Modelling





High Fidelity IMEP modelling (turbulence and MHD) T. Luda, to be submitted

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Plasma System: mandatory multi-fidelity, iterative approach for fusion plant design

Plasma System as Part of system code: simplified, ad-hoc parameters, scaling laws. Optimization loops

2D, 3D systems engineering

Design point

High Fidelity Integrated Modelling: Profiles, heating, current profile, stability, exhaust compatibility, etc

Validation against existing experiments

Verification against higher fidelity models
As long as exptal burning plasmas unavailable

STEP [Tholerus NF2024]
SPARC [Muraca NF2025]
ARC [Howard JPP2026]
EU-VNS [Quartararo Mon. S2-019]

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Guidance for improved physics models

Revised plasma performances
Incl. uncertainties

EU-VNS [Quartararo Mon. S2-019]

How to improve/assess fusion plant design robustness?

- **Improve plasma physics description:**

  - **in system code:** reduce ad-hoc parameters and empirical scaling laws usage. Ex. EUROFusion pilot plant VNS design using METIS coupled to MADE [Quartararo Mon. S2-019] to be extended thanks to turbulent/MHD/SOL AI trained surrogates
  - **in flight simulator for kinetic**/magnetic **control:** move from simplified models to physics based ones. NB: Controllability impacts design, ex. accidental reattachment heat flux limit due to strike point sweeping time in EU-DEMO

How to improve/assess fusion plant design robustness?

- **Improve plasma physics description** in system code and in flight simulator for kinetic/magnetic control [Quartararo Mon. S2-019] for a more resilient design

- **Verified, improved physics description of plasma system allows to**
  - **Assess plasma performances incl. uncertainties:** ex. EU-DEMO P_{fus} range 0.8 to 2.2 GW, for ARC P_{fus} range 0.9 to 1.3 GW [Howard JPP2026]
  - **Quantify failure severity:** ex. DEMO class design by system code PROCESS, using:
    - higher fidelity guidance for ad-hoc parameter intervals
    - 8 most uncertain parameters, 2048 samples

    ➢dramatic failure (failure severity up to 10.2) possible

    ➢next: **aiming at resilience-based design optimisation** [Maddock Tue. S2-011]

How to improve/assess fusion plant design robustness?

- **Improve plasma physics description** in system code and in flight simulator for kinetic/magnetic control [Quartararo this conf. S2-019]

- Verified, improved physics description of plasma system allows to assess **plasma performances incl. uncertainties** ex. EU-DEMO P_{fus} range 0.8 to 2.2 GW**, to quantify failure severity**, ex. DEMO class dramatic failure possible [Maddock this conf. S2-011]

- **Validation on Q>5 burning plasmas** ($P_{alpha} > P_{auxiliary}$) **experiments mandatory** before **reliable** design of fusion plant aiming at net electricity